NetCDF Classic and 64-bit Offset File Formats

1 Status of this Memo

This is a description and formal specification of the Unidata network Common Data Form (netCDF) "classic" file format and of a 64-bit offset variant of that format, provided in enough detail to support independent implementations of software to read and write netCDF data.

Distribution of this memo is unlimited.

2 Change Explanation

This is a second draft incorporating minor changes needed to permit netCDF names to begin with a numeric character.

3 Copyright Notice

4 Abstract

This document specifies netCDF file format variants in a way that is independent of I/O libraries designed to read and write netCDF data. The purpose of netCDF is to provide a data model, software libraries, and machine-independent data format for geoscience data. Together, the netCDF interfaces, libraries, and format support the creation, access, and sharing of scientific data.

With suitable community conventions, netCDF can help improve interoperability among data providers, data users, and data services.

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5 Introduction

NetCDF (network Common Data Form) is a data model for array-oriented scientific data, a freely distributed collection of access libraries implementing support for that data model, and a machine-independent format. Together, the interfaces, libraries, and format support the creation, access, and sharing of scientific data.

NetCDF data is intended to make possible the creation of collections of data that are:

- *Self-Describing:* NetCDF datasets include information about the data they contain.
- *Portable:* Computers with different ways of storing integers, characters, and floating-point numbers can access netCDF data.
- *Direct-access:* A small subset of a large data set may be accessed efficiently, without first reading through all the preceding data.
- *Appendable:* Data may be appended to a properly structured netCDF file without copying the data set or redefining its structure.
- *Sharable:* One writer and multiple readers may simultaneously access the same netCDF file. Using parallel netCDF interfaces, multiple writers may write a file concurrently.
- *Archivable:* Access to current and earlier forms of netCDF data will be supported by current and future versions of the software.

In different contexts, “netCDF” may refer to an abstract data model, a software implementation

with associated application program interfaces (APIs), or a data format. Confusion may easily arise in discussions of different versions of the data models, software, and formats, because the relationship among versions of these entities is more complex than a simple one-to-one correspondence by version. For example, compatibility commitments require that new versions of the software support all previous variants of the format and data model.

To avoid this potential confusion, we assign distinct names to versions of the formats, data models, and software releases that will be used consistently in the remainder of this document.

This document formally specifies two format variants, the ***classic format*** and the ***64-bit offset format*** for netCDF data. It also informally describes two additional format variants, the ***netCDF-4 format*** and the ***netCDF-4 classic model format***.

The classic format was the only format for netCDF data created between 1989 and 2004 by various versions of the reference software from Unidata. In 2004, the 64-bit offset format variant was introduced for creation of and access to much larger files. The reference software, available for C-based and Java-based programs, supported use of the same APIs for accessing either classic or 64-bit offset files, so programs reading the files would not have to depend on which format was used.

There are only two netCDF data models, the ***classic model*** and the ***enhanced model***. The classic model is the simpler of the two, and is used for all data stored in classic format, 64-bit offset format, or netCDF-4 classic model format. The enhanced model (also referred to as the netCDF-4 data model) was introduced in netCDF-4 as an extension of the classic model that adds more powerful forms of data representation and data types at the expense of some additional complexity. Although data represented with the classic model can also be represented using the enhanced model, datasets that use features of the enhanced model, such as user-defined nested data types, cannot be represented with the classic model. Use of added features of the enhanced model requires that data be stored in the netCDF-4 format.

Versions 1.0 through 3.5 of the Unidata C-based reference software, released between 1989 and 2000, supported only the classic data model and classic format. Version 3.6, released in late 2004, first provided support for the 64-bit offset format, but still used the classic data model. With version 4.0, released in 2008, the enhanced data model was introduced along with the two new HDF5-based format variants, the netCDF-4 format and the netCDF-4 classic model format. Evolution of the data models, formats, and APIs will continue the commitment to support all previous netCDF data models, data format variants, and APIs in future software releases.

Use of the HDF5 storage layer in netCDF-4 software provides features for improved performance, independent of the data model used, for example compression and dynamic schema changes. Such performance improvements are available for data stored in the netCDF-4 classic model format, even when accessed by programs that only support the classic model.

A full specification of the two netCDF-4 formats in terms of the underlying HDF5 storage layer is outside the scope of this document. Other related formats not discussed in this document include CDL (“Common Data Language”, the original ASCII form of binary netCDF data), and NcML (NetCDF Markup Language, an XML-based representation for netCDF metadata and data).

Knowledge of format details is not required to read or write netCDF datasets. Software that reads netCDF data using the reference implementation automatically detects and uses the correct version of the format for accessing data. Understanding details may be helpful for understanding performance issues related to disk or server access.

This specification is needed because no standard currently exists that describes the format in sufficient detail for independent implementations of netCDF access software. Making it an ESDS standard provides a reference that precisely documents the netCDF format stored in a multitude of archives. A published reference standard assures the long term usability of netCDF data archives, because it transcends issues concerning the future availability of specific hardware and software.

Such a standard may also encourage increased interoperability of data services, scientific analysis software, and data management software, as current and potential developers learn of the simplicity and representational power of a widely used format.

Limitations of this standard include a lack of precise specification for the new netCDF-4 format (which uses an underlying HDF5 format), lack of description of conventions layers such as the CF Conventions that provide representations for coordinate systems and other abstractions, and absence of detailed examples. Some of these limitations may be overcome in future versions of the standard.

The netCDF reference library, developed and supported by Unidata, is written in C, with Fortran77, Fortran90, and C++ interfaces. A number of community and commercially supported interfaces to other languages are also available, including IDL, Matlab, Perl, Python, and Ruby. An independent implementation, also developed and supported by Unidata, is written entirely in Java.

5.1 The Classic Data Model

The classic model represents information in a netCDF data set using *dimensions*, *variables*, and *attributes*, to capture the meaning of array-oriented scientific data. Figure 1 presents a simplified UML diagram of the classic data model.

Variables hold data values. In the classic model, a variable can hold a multidimensional array of values of the same type. A variable has a name, type, shape, attributes, and values. The shape of a variable is specified with a list of zero or more dimensions:

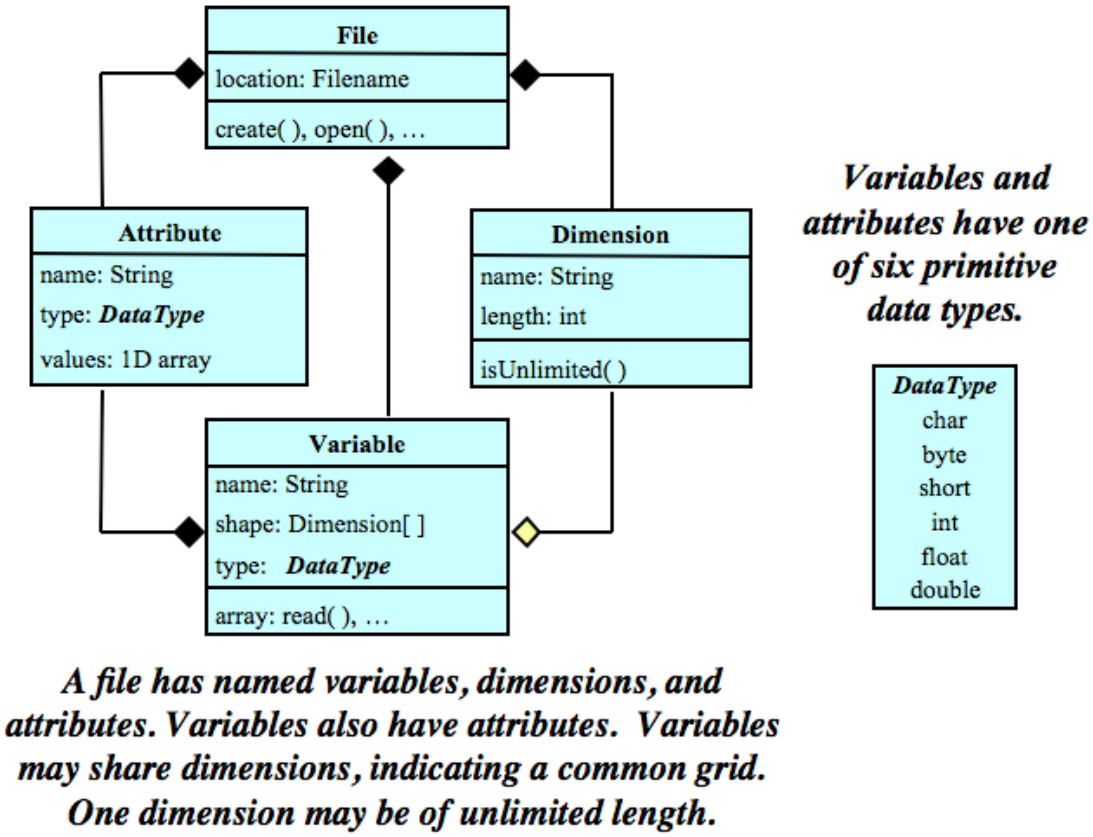
- 0 dimensions: a *scalar variable* with only one value
- 1 dimension: a 1-D (vector) variable
- 2 dimensions: a 2-D (matrix or grid) variable
- ...

Dimensions are used to specify variable shapes, common grids, and coordinate systems. A dimension has a name and a length. Dimensions may be shared among variables, indicating a common grid. Dimensions may be associated with *coordinate variables* to identify coordinate axes. In the classic model, at most one dimension can have the *unlimited* length, which means

variables can grow along that dimension. *Record dimension* is another term for an unlimited dimension. (In the enhanced model, multiple dimensions can have the unlimited length.)

Attributes hold metadata (data about data). An attribute contains information about properties of a variable or an entire data set. Variable attributes may be used to specify properties such as units. Attributes that apply to a whole data set, also called *global attributes*, may be used to record properties of all the data in a file, such as processing history or conventions used. An attribute may have zero, one, or multiple values (1-D), but attributes cannot be multidimensional. NetCDF conventions are defined primarily in terms of attributes. Thus the names of attributes are typically standardized in conventions rather than the names of variables.

Figure 1 The netCDF "classic" data model



For a more comprehensive explanation of the netCDF data model, see the NetCDF User's Guide [1] or the online NetCDF Workshop for Developers and Data Providers [3].

5.2 The NetCDF-4 Format

The netCDF-4 format implements and expands the classic model by using an enhanced version of HDF5 [7] as the storage layer. Use is made of features that are only available in HDF5 version 1.8 and later.

Using HDF5 as the underlying storage layer, netCDF-4 files remove many of the restrictions for classic and 64-bit offset files. The richer enhanced model supports user-defined types and data structures, hierarchical scoping of names using groups, more primitive types including strings, larger variable sizes, and multiple unlimited dimensions. The underlying HDF5 storage layer also supports per-variable compression, multidimensional tiling, and efficient dynamic schema changes, so that data need not be copied when adding new variables to a file schema.

Although every file in netCDF-4 format is an HDF5 file, there are HDF5 files that are not netCDF-4 format files, because the netCDF-4 format intentionally uses a limited subset of the HDF5 data model and file format features. Some HDF5 features not supported in the netCDF enhanced model and netCDF-4 format include non-hierarchical group structures, HDF5 reference types, multiple links to a data object, user-defined atomic data types, stored property lists, more permissive rules for data object names, the HDF5 date/time type, and attributes associated with user-defined types.

5.3 The NetCDF-4 Classic Model Format

Every classic and 64-bit offset file can be represented as a netCDF-4 file, with no loss of information. There are some significant benefits to using the simpler netCDF classic model with a netCDF-4 file format. For example, software that writes or reads classic model data can write or read netCDF-4 classic model format data by recompiling/relinking to a netCDF-4 API library, with no or only trivial changes needed to the program source code. The netCDF-4 classic model format supports this usage by enforcing rules on what functions may be called to store data in the file, to make sure its data can be read by older netCDF applications (when relinked to a netCDF-4 library).

Writing data in this format prevents use of enhanced model features such as groups, added primitive types not available in the classic model, and user-defined types. However performance features of the netCDF-4 formats that do not require additional features of the enhanced model, such as per-variable compression and chunking, efficient dynamic schema changes, and larger variable size limits, offer potentially significant performance improvements to readers of data stored in this format, without requiring program changes.

6 Classic Format Specification

6.1 Informal Description

To make the formal description more easily understood, we begin with an informal description of the classic format, which also applies to the 64-bit offset variant. Understanding the format at this level can make clear which netCDF operations are expensive, for example adding a new variable to an existing file.

A classic or 64-bit offset file is stored in three parts:

1. The *header*, containing information about dimensions, attributes, and variables

2. The *fixed-size data*, containing data values for variables that don't have an unlimited dimension
3. The *record data*, containing data values for variables that have an unlimited dimension

The header has information about the dimensions, variables, and attributes, including all the attribute values. There is typically little extra space in the header, unless such space is reserved when the file is created. This is why the dimensions, variables, and attributes in a netCDF file are typically defined when the file is created, before any data is written. Operations that require the header to grow force moving all the data by copying it.

Only one unlimited dimension, the *record dimension*, is permitted in classic model files. The current size of the record dimension is stored in the header, which specifies how many records the file contains. New data may be efficiently added to *record variables* (variables that use the record dimension in specifying their shape) along the record dimension.

The fixed-size data part has all the data for each non-record variable. The data for each variable is stored contiguously, in row-major order for multi-dimensional variables.

Each record in the record data part is similar to the fixed-size data part, containing all the data for that record for each record variable. Each record's worth of data for each record variable is stored contiguously, in row major order for multidimensional variables. All records are the same size, because they each contain all the data for a particular record for each record variable.

6.2 Formal Specification of the Classic Format

To present the format more formally, we use a BNF grammar notation. In this notation:

- Non-terminals (entities defined by grammar rules) are in lower case.
- Terminals (atomic entities in terms of which the format specification is written) are in upper case, and are specified literally as US-ASCII characters within single-quote characters or are described with text between angle brackets (‘<’ and ‘>’).
- Optional entities are enclosed between braces (‘`[`’ and ‘`]`’).
- A sequence of zero or more occurrences of an entity is denoted by ‘`[entity ...]`’.
- A vertical line character (‘`|`’) separates alternatives. Alternation has lower precedence than concatenation.
- Comments follow ‘`//`’ characters.
- A single byte that is not a printable character is denoted using a hexadecimal number with the notation ‘`\xDD`’, where each `D` is a hexadecimal digit.
- A literal single-quote character is denoted by ‘`\'`’, and a literal back-slash character is denoted by ‘`\\`’.

Following the grammar, a few additional notes are included to specify format characteristics that are impractical to capture in a BNF grammar, and to note some special cases for implementers. Comments in the grammar point to the notes and special cases, and help to clarify the intent of elements of the format.

```
netcdf_file  = header  data
header       = magic  numrecs  dim_list  gatt_list  var_list
magic        = 'C'  'D'  'F'  VERSION
VERSION      = \x01 |                      // classic format
               \x02                        // 64-bit offset format
numrecs      = NON_NEG | STREAMING         // length of record dimension
dim_list     = ABSENT | NC_DIMENSION  nelems  [dim ...]
gatt_list    = att_list                    // global attributes
att_list     = ABSENT | NC_ATTRIBUTE  nelems  [attr ...]
var_list     = ABSENT | NC_VARIABLE   nelems  [var ...]
ABSENT       = ZERO  ZERO                  // Means list is not present
ZERO         = \x00 \x00 \x00 \x00         // 32-bit zero
NC_DIMENSION = \x00 \x00 \x00 \x0A         // tag for list of dimensions
NC_VARIABLE  = \x00 \x00 \x00 \x0B         // tag for list of variables
NC_ATTRIBUTE = \x00 \x00 \x00 \x0C         // tag for list of attributes
nelems       = NON_NEG       // number of elements in following sequence
dim          = name  dim_length
name         = nelems  namestring
                    // Names a dimension, variable, or attribute.
                    // Names should match the regular expression
                    //([a-zA-Z0-9_]|{MUTF8})([^\x00-\x1F/\x7F-\xFF]|{MUTF8})*
                    // For other constraints, see “Note on names”, below.
namestring   = ID1 [IDN ...]
ID1          = alphanumeric | '_'
IDN          = alphanumeric | special1 | special2
alphanumeric = lowercase | uppercase | numeric | MUTF8
lowercase    = 'a'|'b'|'c'|'d'|'e'|'f'|'g'|'h'|'i'|'j'|'k'|'l'|'m'|
               'n'|'o'|'p'|'q'|'r'|'s'|'t'|'u'|'v'|'w'|'x'|'y'|'z'
uppercase    = 'A'|'B'|'C'|'D'|'E'|'F'|'G'|'H'|'I'|'J'|'K'|'L'|'M'|
               'N'|'O'|'P'|'Q'|'R'|'S'|'T'|'U'|'V'|'W'|'X'|'Y'|'Z'
numeric      = '0'|'1'|'2'|'3'|'4'|'5'|'6'|'7'|'8'|'9'

                           // special1 chars have traditionally been
                           // permitted in netCDF names.
special1     = '_'|'.'|'@'|'+'|'-'
```

```
                              // special2 chars are recently permitted in
                              // names (and require escaping in CDL).
                              // Note: '/' is not permitted.
special2      = ' ' | '!' | '"' | '#'  | '$' | '%' | '&' | '\'' |
                '(' | ')' | '*' | ','  | ':' | ';' | '<' | '='  |
                '>' | '?' | '[' | '\\' | ']' | '^' | '`' | '{'  |
                '|' | '}' | '~'
MUTF8         = <multibyte UTF-8 encoded, NFC-normalized Unicode character>
dim_length    = NON_NEG       // If zero, this is the record dimension.
                              // There can be at most one record dimension.
attr          = name  nc_type  nelems  [values ...]
nc_type       = NC_BYTE | NC_CHAR | NC_SHORT | NC_INT | NC_FLOAT | NC_DOUBLE
var           = name  nelems  [dimid ...]  vatt_list  nc_type  vsize  begin
                              // nelems is the dimensionality (rank) of the
                              // variable: 0 for scalar, 1 for vector, 2
                              // for matrix, ...
dimid         = NON_NEG       // Dimension ID (index into dim_list) for
                              // variable shape.  We say this is a "record
                              // variable" if and only if the first
                              // dimension is the record dimension.
vatt_list     = att_list      // Variable-specific attributes
vsize         = NON_NEG       // Variable size.  If not a record variable,
                              // the amount of space in bytes allocated to
                              // the variable's data.  If a record variable,
                              // the amount of space per record.  See “Note on
                              // vsize” below.
begin         = OFFSET        // Variable start location.  The offset in
                              // bytes (seek index) in the file of the
                              // beginning of data for this variable.
data          = non_recs  recs
non_recs      = [vardata ...] // The data for all non-record variables,
                              // stored contiguously for each variable, in
                              // the same order the variables occur in the
                              // header.
vardata       = [values ...]  // All data for a non-record variable, as a
                              // block of values of the same type as the
```

```
                              // variable, in row-major order (last
                              // dimension varying fastest).
recs          = [record ...]  // The data for all record variables are
                              // stored interleaved at the end of the
                              // file.
record        = [varslab ...] // Each record consists of the n-th slab
                              // from each record variable, for example
                              // x[n,...], y[n,...], z[n,...] where the
                              // first index is the record number, which
                              // is the unlimited dimension index.
varslab       = [values ...]  // One record of data for a variable, a
                              // block of values all of the same type as
                              // the variable in row-major order (last
                              // index varying fastest).
values        = bytes | chars | shorts | ints | floats | doubles
string        = nelems  [chars]
bytes         = [BYTE ...]  padding
chars         = [CHAR ...]  padding
shorts        = [SHORT ...]  padding
ints          = [INT ...]
floats        = [FLOAT ...]
doubles       = [DOUBLE ...]
padding       = <0, 1, 2, or 3 bytes to next 4-byte boundary>
                              // Header padding uses null (\x00) bytes.  In
                              // data, padding uses variable's fill value.
                              // See “Note on padding” below for a special
                              // case.
NON_NEG       = <non-negative INT>
STREAMING     = \xFF \xFF \xFF \xFF   // Indicates indeterminate record
                                      // count, allows streaming data
OFFSET        = <non-negative INT> |  // For classic format or
                <non-negative INT64>  // for 64-bit offset format
BYTE          = <8-bit byte>          // See “Note on byte data”, below.
CHAR          = <8-bit byte>          // See “Note on char data”, below.
SHORT         = <16-bit signed integer, Bigendian, two's complement>
INT           = <32-bit signed integer, Bigendian, two's complement>
```

```
INT64        = <64-bit signed integer, Bigendian, two's complement>
FLOAT        = <32-bit IEEE single-precision float, Bigendian>
DOUBLE       = <64-bit IEEE double-precision float, Bigendian>
                              // following type tags are 32-bit integers
NC_BYTE      = \x00 \x00 \x00 \x01       // 8-bit signed integers
NC_CHAR      = \x00 \x00 \x00 \x02       // text characters
NC_SHORT     = \x00 \x00 \x00 \x03       // 16-bit signed integers
NC_INT       = \x00 \x00 \x00 \x04       // 32-bit signed integers
NC_FLOAT     = \x00 \x00 \x00 \x05       // IEEE single precision floats
NC_DOUBLE    = \x00 \x00 \x00 \x06       // IEEE double precision floats
                            // Default fill values for each type, may be
                            // overridden by variable attribute named
                            // '_FillValue', see "Note on fill values", below
FILL_BYTE    = \x81                      // (signed char) -127
FILL_CHAR    = \x00                      // null byte
FILL_SHORT   = \x80 \x01                 // (short) -32767
FILL_INT     = \x80 \x00 \x00 \x01       // (int) -2147483647
FILL_FLOAT   = \x7C \xF0 \x00 \x00       // (float) 9.9692099683868690e+36
FILL_DOUBLE  = \x47 \x9E \x00 \x00 \x00 \x00 //(double)9.9692099683868690e+36
```

Note on `vsize`: This number is the product of the dimension lengths (omitting the record dimension) and the number of bytes per value (determined from the type), increased to the next multiple of 4, for each variable. If a record variable, this is the amount of space per record. The netCDF "record size" is calculated as the sum of the `vsize`'s of all the record variables.

The `vsize` field is actually redundant, because its value may be computed from other information in the header. The 32-bit `vsize` field is not large enough to contain the size of variables that require more than 2^{32} - 4 bytes, so 2^{32} - 1 is used in the `vsize` field for such variables.

Note on names: Earlier versions of the netCDF C-library reference implementation enforced a more restricted set of characters in creating new names, but permitted reading names containing arbitrary bytes. This RFC extends the permitted characters in names to include multi-byte UTF-8 encoded[7] Unicode[4] and additional printing characters from the US-ASCII alphabet. The first character of a name must be alphanumeric, a multi-byte UTF-8 character, or '_' (traditionally reserved for names with meaning to implementations, such as the "`_FillValue`" attribute). Subsequent characters may also include printing special characters, except for '/' which is not allowed in names. Names that have trailing space characters are also not permitted.

Implementations of the netCDF classic and 64-bit offset format must ensure that names are normalized according to Unicode NFC normalization rules [5] during encoding as UTF-8 for storing in the file header. This is necessary to ensure that gratuitous differences in the

representation of Unicode names do not cause anomalies in comparing files and querying data objects by name.

Note on streaming data: The largest possible record count, 2^{32}-1, is reserved to indicate an indeterminate number of records. This means that the number of records in the file must be determined by other means, such as reading them or computing the current number of records from the file length and other information in the header. It also means that the `numrecs` field in the header will not be updated as records are added to the file.

Note on padding: In the special case of only a single record variable of character, byte, or short type, no padding is used between data values.

Note on byte data: It is possible to interpret byte data as either signed (-128 to 127) or unsigned (0 to 255). When reading byte data through an interface that converts it into another numeric type, the default interpretation is signed. There are various attribute conventions for specifying whether bytes represent signed or unsigned data, but no standard convention has been established. The variable attribute "`_Unsigned`" is reserved for this purpose in future implementations.

Note on char data: Although the characters used in netCDF names must be encoded as UTF-8, character data may use other encodings. The variable attribute "`_Encoding`" is reserved for this purpose in future implementations.

Note on fill values: Because data variables may be created before their values are written, and because values need not be written sequentially in a netCDF file, default "fill values" are defined for each type, for initializing data values before they are explicitly written. This makes it possible to detect reading values that were never written. The variable attribute "`_FillValue`", if present, overrides the default fill value for a variable. If `_FillValue` is defined then it should be scalar and of the same type as the variable.

Fill values are not required, however, because netCDF libraries have traditionally supported a "no fill" mode when writing, omitting the initialization of variable values with fill values. This makes the creation of large files faster, but also eliminates the possibility of detecting the inadvertent reading of values that were not written.

6.3 The 64-bit Offset Format Variant

The netCDF 64-bit offset format differs from the classic format only in the `VERSION` byte, `\x02` instead of `\x01`, and the `OFFSET` entity, a 64-bit instead of a 32-bit offset from the beginning of the file.

This small format change permits much larger files, but there are still some practical size restrictions. Each fixed-size variable and the data for one record's worth of each record variable are still limited in size to a little less that 4 GiB. The rationale for this limitation is to permit aggregate access to all the data in a netCDF variable (or a record's worth of data) on 32-bit platforms.

7 References

Normative References

[4] *The Unicode Standard, Version 5.0, Fifth Edition,* The Unicode Consortium, Addison-Wesley Professional, 2006.

[5] *Unicode Standard Annex #15. Unicode Normalization Forms*, The Unicode Consortium, http://www.unicode.org/reports/tr15/

[6] HDF5 Library Documentation, Release 1.8.0, February 2008.

[7] RFC3629 - UTF-8, a transformation format of ISO 10646, F. Yergeau, http://ietfreport.isoc.org/idref/rfc3629/

Informative References

[1] *NetCDF User's Guide for version 3.6.3*, R. Rew, H. Davies, G. Davis, S. Emmerson, and E. Hartnett. (UCAR/Unidata Program Center, Boulder, Colorado), 2008 edition. http://www.unidata.ucar.edu/netcdf/old_docs/docs_3_6_3/netcdf.html

[2] *NetCDF User's Guide (most recent version)*, R. Rew, H. Davies, G. Davis, S. Emmerson, and E. Hartnett. (UCAR/Unidata Program Center, Boulder, Colorado), 2008 edition. http://www.unidata.ucar.edu/netcdf/docs/netcdf.html

[3] NetCDF Workshop for Developers and Data Providers, Russ Rew and Ed Hartnett, URL: http://www.unidata.ucar.edu/netcdf/workshops/2007/

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9 Appendix A

Glossary of acronyms

Example:

Acronym	Description
ASCII:	American Standard Code for Information Interchange

BNF:	Backus-Naur Form
CDL:	netCDF Common Data Language
GiB:	GibiByte, 2^{30} bytes which is 1,073,741,824 bytes
HDF5:	Hierarchical Data Format, version 5
netCDF:	network Common Data Form
NFC:	Unicode Normalization Form C
NcML:	NetCDF Markup Language
UML:	Unified Modeling Language
UTF-8:	Unicode Transfer Format, 8 bit
XML:	eXtensible Markup Language